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FFT Space Processing for the ACF of SPREE Particle Flux Measurements

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This manuscript is intended to describe the processing and the X Window display of the Fourier transform of the autocorrelation measurement from the SPREE particle correlator Experiment (SPACE). The SPREE was flown aboard the Space Shuttle Atlantis flight STS 46 as part of the Tethered Satellite System (TSS 1). SPACE is essentially a signal processing unit that analyzes the particle fluxes from the SPREE electrostatic analyzers (ESA) to identify wave-particle modulations. The SPACE outputs ACF data containing information on the wave particle modulations. An efficient way to examine these modulations is by means of the Fourier Transform techniques. The SPACE Fourier analysis and display tools, which are part of the SIDAT package, are presented. These tools use color raster graphics and text displays based on the X11 and XView X Window System libraries on Sun SPARC workstations.

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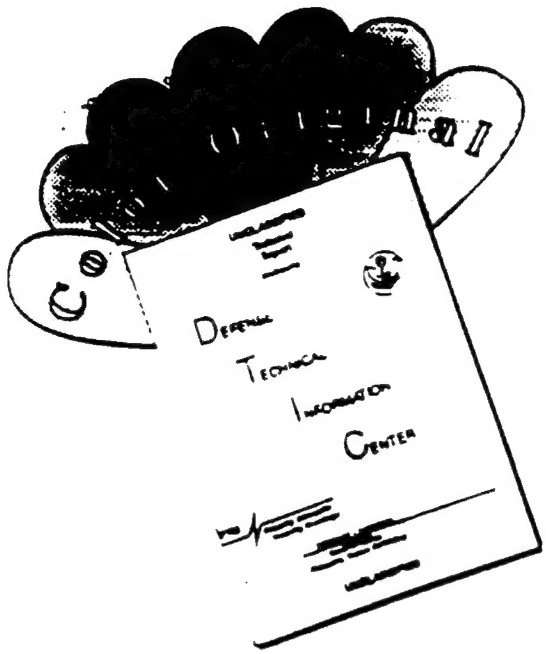

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We are very grateful to M. R. Oberhardt and Dr. D. A. Hardy of Phillips Laboratory, Hanscom AFB, and Prof. M. P. Gough of the University of Sussex, U. K., for their guidance and suggestions in the development of the SPACE FFT processing tools. We are grateful to C. J. Roth of Radex, Inc., Bedford, MA for supplying many of the X Window display routines and the SPACE data format.

LIST OF ACRONYMS

ACF	Autocorrelation Function
ASCII	American Standard Code Information Interchange
DFT	Discrete Fourier Transform
ESA	Electrostatic Analyzer
FDR	Flight Data Recorder
FFT	Fast Fourier Transform
FPEG	Fast Pulsed Electron Generator
HF	High Frequency
LF	Low Frequency
SIDAT	SPREE Interactive Data Analysis Tool
SPACE	SPREE Particle Correlator Experiment
SPREE	Shuttle Potential and Return Electron Experiment
STS	Space Transportation System
UT	Universal Time
WPI	Wave Particle Interaction

1. INTRODUCTION

During the Space Shuttle Atlantis flight STS 46 mission, particle flux measurements from the Shuttle Potential and Return Electron Experiment (SPREE) electrostatic analyzers (ESA) were fed through the Space Particle Correlator Experiment (SPACE) in order to identify the wave particle modulations or the wave particle interactions (WPIs) [*Gough, et al.*, 1994]. SPACE is essentially a signal processing unit that detects the WPIs Modulations. *Gough, et al.* [1991] used a bunching technique to build the autocorrelation functions (ACF) of the particle events for an accumulation period that depended on the ESA sweep rate. There were two modes: a slow mode of 1 sweep per second and a fast mode of 8 sweeps per second. The accumulation period was 3 seconds in the slow mode or 12 seconds in the fast mode. The accumulation period is divided evenly among the 32 energy channels. To construct the ACFs, the bunching technique is used. The bunching technique, as explained in *Gough, et al.* [1990], is the times between particle arrivals measured in units of counts of a clock running at twice the maximum frequency of interest. For each arrival of a particle at a given energy, the lag or bin of the ACFs corresponding to the time C (in units of the clock rate), which elapsed from the previously detected particle in the same energy channel, is incremented by one count. This counting process, used in building the ACFs in all energy channels, is repeated for the duration of the accumulation period. For the high frequency cases, 64 ACF lags were considered (i.e., C ranges from 1 to 64 in clock time units), whereas for the low frequency case, only 32 ACF lags were recorded.

SPACE had frequency ranges of 0-10KHz, 0-5 KHz, and 0-1.2 KHz for low frequency electron and ion fluxes; and 0-10MHz, 0-2.5MHz, and 0.625 MHz for high frequency electron fluxes. The Fourier transform approach is suitable for examining the signatures in these frequency bands. Fast Fourier transform (FFT) of the HF or LF ACFs yields a 32-point frequency spectrum for each energy channel during each accumulation period. Frequency resolution is the 1/32th of the maximum frequency; viz. 0.3125 KHz for a 10 MHz frequency or 37.5 Hz for a 1.2 KHz.

The SPACE processing programs are part of the SIDAT Xlib and XView X Window package [*Roth and Bonito*, 1992]. The display screens utilize the Xlib graphics primitives and the XView Graphical User Interface toolkit. How the SPACE processing programs are incorporated in SIDAT is explained in detail in this reference.

The processing and display tool access shared database, which was collected during the SPREE instrument aboard the STS 46 spacecraft by means of two AMPTEK Field Data Recording units (FDR1 and FDR2). The field and processed data bases are located on the SUN SPARC station. This tool is used in the analysis of the post-flight data by specifying the time and the range of modulations in the particle fluxes. The SPACE ACFs are then processed with optional processing steps before computing their Fourier transforms. The processing option enables the user to remove trends and spikes in the correlation sequences. A trend in the ACF tends to concentrate all of its spectrum energy in the low frequency bands. A spike, on the other hand,

will cause the spectrum energy at high frequency bands to become significant. Further, this may cause fold-over distortion if no proper tapering is applied to the ACFs. This is an artifact whereby the high spectral frequencies leak over to the low frequency band when the FFT transform operation is performed.

2. SPACE RELATIONSHIP TO SPREE

The Shuttle Potential and Return Electron Experiment (SPREE) on flight STS 46 had two multi-angular electrostatic analyzers (ESA) to measure particle fluxes. These data were fed through the Space Particle Correlator Experiment (SPACE) in order to identify the wave particle modulations. SPACE was designed to detect these HF and LF wave modulations. *Gough, et al.* [1991] used a bunching technique to build the autocorrelations (ACF) of the particle events for an accumulation time that depended on the ESA sweep rate. The accumulation times were either 3 seconds or 12 seconds. The ACFs are constructed by adding one count to the lag number (in terms of the clock rate) that separates two simultaneous particle events.

The pair of SPREE ESA units measured the characteristics and number of detected ion and electron particles. The energy range of these particles is from 10 eV to 10KeV. There are two modes, one with 1 sweep per second, and the other with 8 sweeps per second. The data from the SPREE analyzers are applied to the SPACE onboard particle correlator, which performed an autocorrelation on the data for specified accumulation times.

The SPACE processing and viewing options are shown in Figure 1. They are part of the SIDAT X Window package [*Roth and Bonito*, 1992]. In this report, the five bottom options are described; viz. FFT SPACE LF, FFT SPACE HF, FFT SPACE SURVEY, FFT Tool SPACE LF, FFT Tool SPACE HF. The other options were discussed in the named reference.

3. SPACE LF FFT WINDOW

The low Frequency FFT window displays a color raster image of energy versus frequency of the Discrete Fourier Transform (DFT) of ACF data as illustrated in Figure 2. The energy range is from 10 eV to 10 KeV. In the low frequency mode, twelve raster images are shown representing data from ESA A and ESA B, for both ion and electron fluxes. These are indicated by SPREE unit numbers whereby units 0 through 2 represent the ESA A ion data, units 3 through 5 represent ESA A electron data, units 6 through 8 represent the ESA B ion data, and units 9 through 11 represent ESA B electron data.

The pull-down menu of the command panel provides the user with several options; one of which is the time of measurements. A particular time can be chosen from the standard start time window. Alternatively, pressing the "Alter" button pops up the standard selection window for

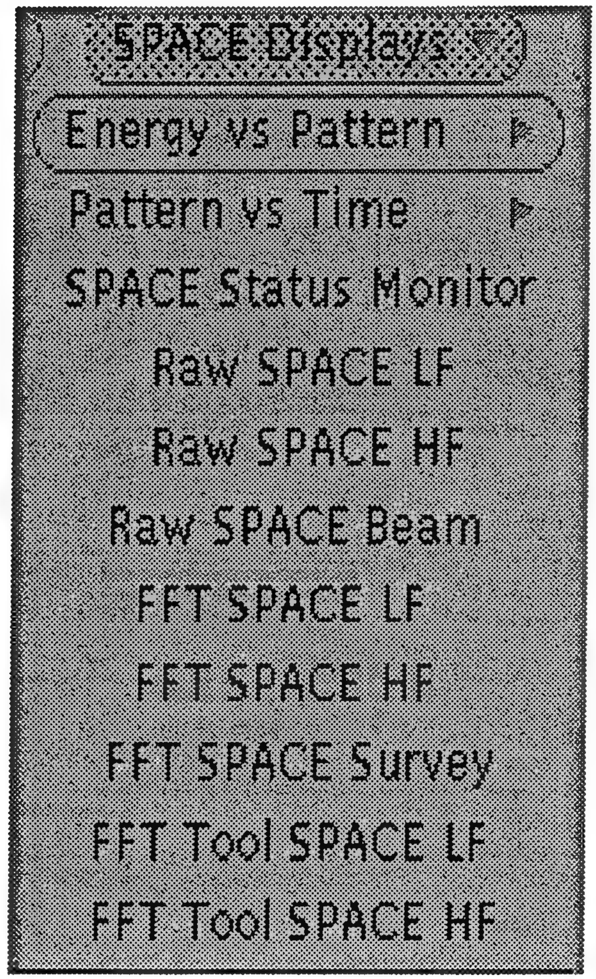

Figure 1. X Window command panel for SPACE processing and display.

the time to be selected by scrolling the day, hour, minute, and second lists. Once a desired time is selected, pressing the "Go" button will begin the processing and viewing of the data. Figure 2 shows the 12 images for times between 20:08:40 and 20:08:44 on August 3, 1992. The normalized FFT Amplitude is represented by a 16-color display in a linear scale, corresponding to a range from 0 to 8. Also displayed on the drawable window are the frequency range, the zone group, and the sweep rate. In Figure 2, the maximum frequency is 10 KHz in a fast mode and zone group 3.

A specific energy level and unit from one of the 12 raster images can be picked to display the line plots of both the ACFs and their Fourier transforms in the bottom of the drawable window. In Figure 2, the line plots are those of the energy bin 2 corresponding to 14.1 eV, and ESA A electron unit # 4. The energy bin and the unit number can be selected from "LF Unit" button and the "Energy Step" button from the text window. Then enabling the "Line Plot" button will display the line plots as shown in Figure 2. Alternatively, clicking with the right-hand mouse button on any of the raster images displays the particular autocorrelation and spectrum line plots for that unit and energy level, as shown in Figure 2. In addition, scrolling the mouse button over the ACF or FFT line plots will display the lag or spectral number and the value of ACF or FFT at that number.

Additional buttons shown in Figure 2 are the "Icon" button, to close the window, and the "Quit" button, to terminate and quit the window.

4. SPACE HF FFT WINDOW

The High Frequency (HF) FFT window display is similar to the LF FFT window display. The only difference is the number of units. Since only electron data are processed in the HF case, there are only six raster images instead of twelve LF raster images, representing data from both the ESA A and ESA B electron fluxes. These are indicated by SPREE unit numbers, whereby units 0 through 2 represent the ESA A data, and units 3 through 5 for ESA B electron data.

The pull-down menu of the command panel provides the options described in the previous section. Figure 3 shows the 6 color raster images for times between 20:08:34 and 20:08:44 on August 3, 1992. The normalized FFT Amplitude is represented by a 16-color display in a linear scale, corresponding to a range from 0 to 16. Also displayed on the drawable window are the frequency range 0-10 MHz, the zone group zg=3, and the sweep rate, which is in a fast mode.

A specific energy level and unit from one of the raster images can be picked to display the line plots of both the ACFs and their Fourier transforms in the bottom of the drawable window. In Figure 3, the line plots are those of the energy bin 20 corresponding to 0.83 KeV, and ESA A electron unit # 1. The energy bin and the unit number can be selected from the "HF Unit" button and the "Energy Step" button from the text window. Then enabling the "Line Plot" button will display the line plots as shown in Figure 3. Alternatively, clicking with the right-

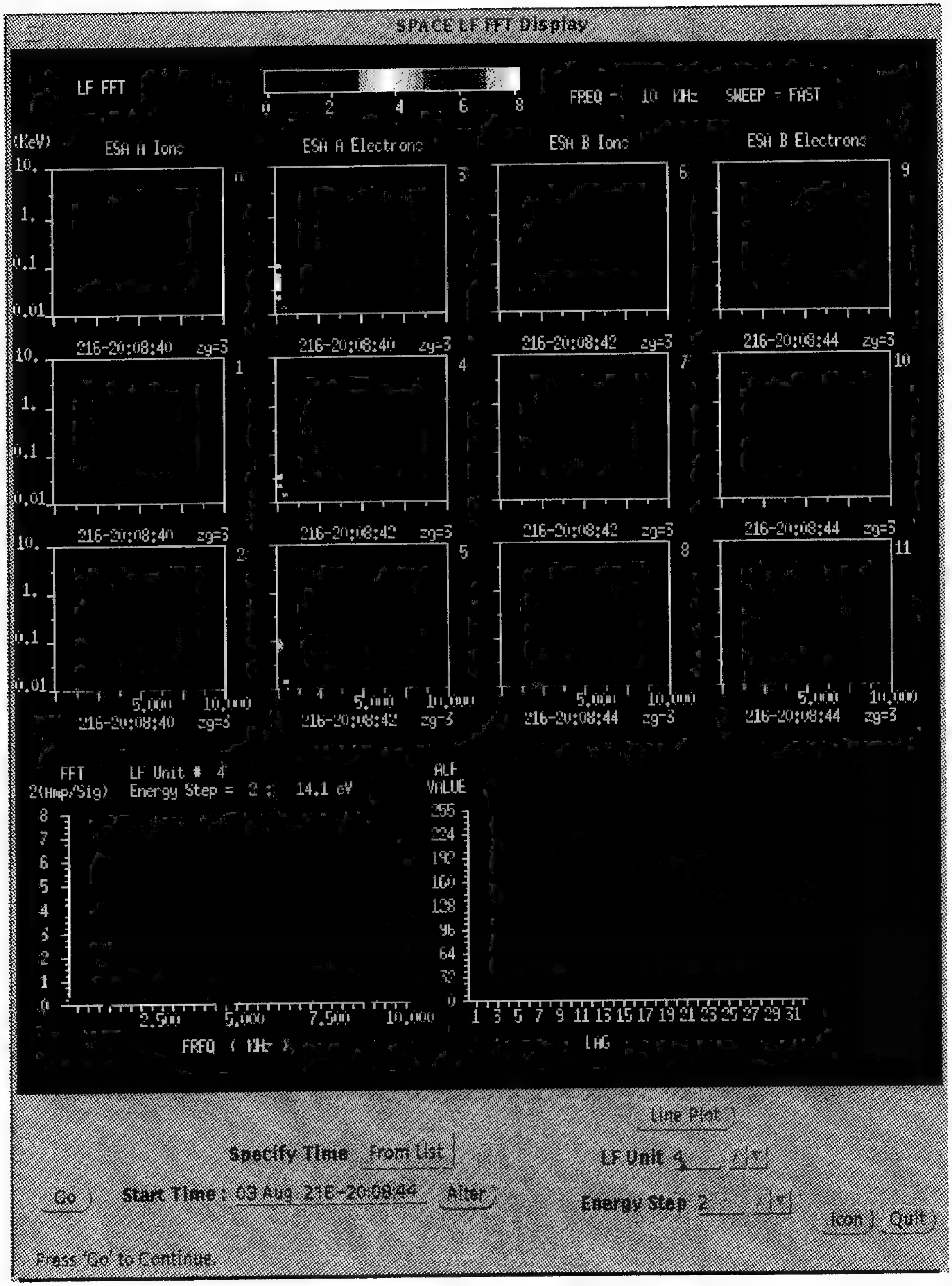

Figure 2. SPACE FFT color raster images and FFT and ACF line plots for LF ACF on August 3, 1992 at 20:08.

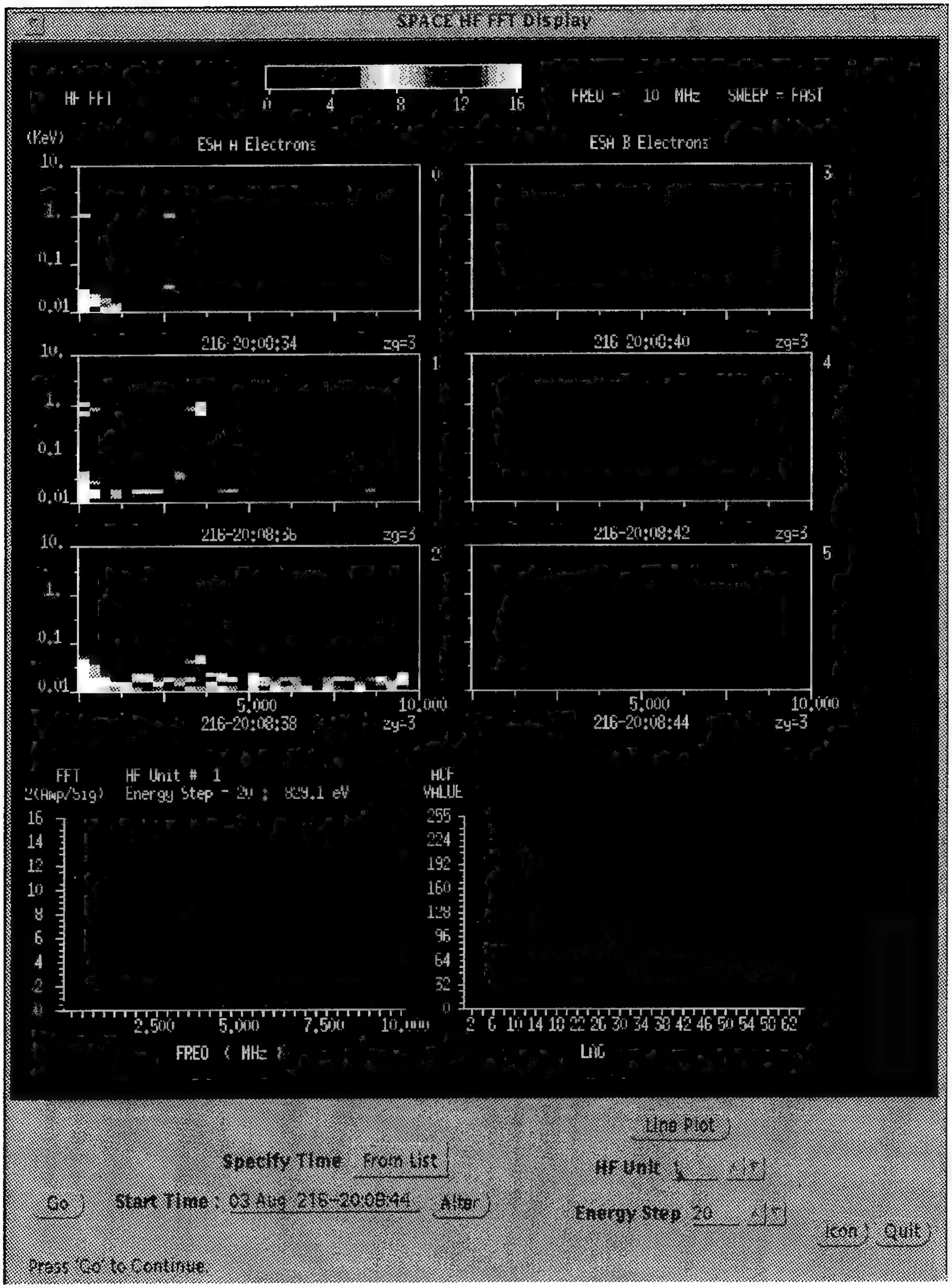

Figure 3. SPACE FFT color raster images and FFT and ACF line plots for HF ACF on August 3, 1992 at 20:08.

hand mouse button on any of the raster images displays the particular ACF and FFT line plots for that unit and energy level, as shown in Figure 3. In addition, scrolling the mouse button over the ACF or FFT line plots will display the lag or spectral number and the value of ACF or FFT at that position.

5. LF AND HF FFT TOOL WINDOW

Both the low and high frequency FFT Tool has 3 drawable windows displaying line plots for a specified energy and unit number. Several buttons on the command panel provide the user with several options, such as the time of measurements, and a specific energy level and unit of the raw ACF data, the processed ACF data, and the normalized FFT Amplitude line plot.

The display window is initiated by choosing a particular time from the standard start time window and with the "NoPlot" option. The "NoPlot" option enables one to move to the specified time without processing the data in the intermediate time interval. This will obviously advance to the desired time a lot faster. The user then presses the "Go" button to advance to the requested time. Once the Go button is released, the user then clicks on the "NoPlot" button, which toggles to a "Plot" button, and the line plots are shown in all three windows. Figures 4 and 5 show the LF and HF FFT display tool. The time selected for LF FFT Tool is 20:09:19 on August 3, 1992, and the time for HF FFT Tool is 20:08:37. Also displayed on the drawable window are the frequency range, the zone group, and the sweep rate. In Figure 4, the frequency range is 10 KHz, in fast mode, zone group 4, an energy step of 10 or 86.2 eV and a Sigma value of about 12. In Figure 5, these parameter values are: the HF range is 10 MHz, in fast mode, zone group 3, an energy step of 20 or 0.83 KeV and a Sigma value of about 12.5.

As the mouse is moved over any of the line plots, the plot coordinates are given in the bottom of the corresponding window.

Additional panel buttons shown in Figures 4 and 5 are the "Filter" menu and the "Taper" menu. The "Filter" lists are described in Appendix A. For LF ACF, no despiking or roll-over correction is needed. Detrending to remove the low frequency components, however, may be used, as is done in Figure 4. In Figure 5, the "BOTH" filtering options is selected for the HF FFT display; that is, both despiking and detrending are performed. The despiking operation will remove any spikes or roll-over in the data. Additionally in Figure 5, a Welch taper was chosen to process the ACFs before the Fourier transformation. There are six available taper windows which are commonly used and are discussed in Appendix A.

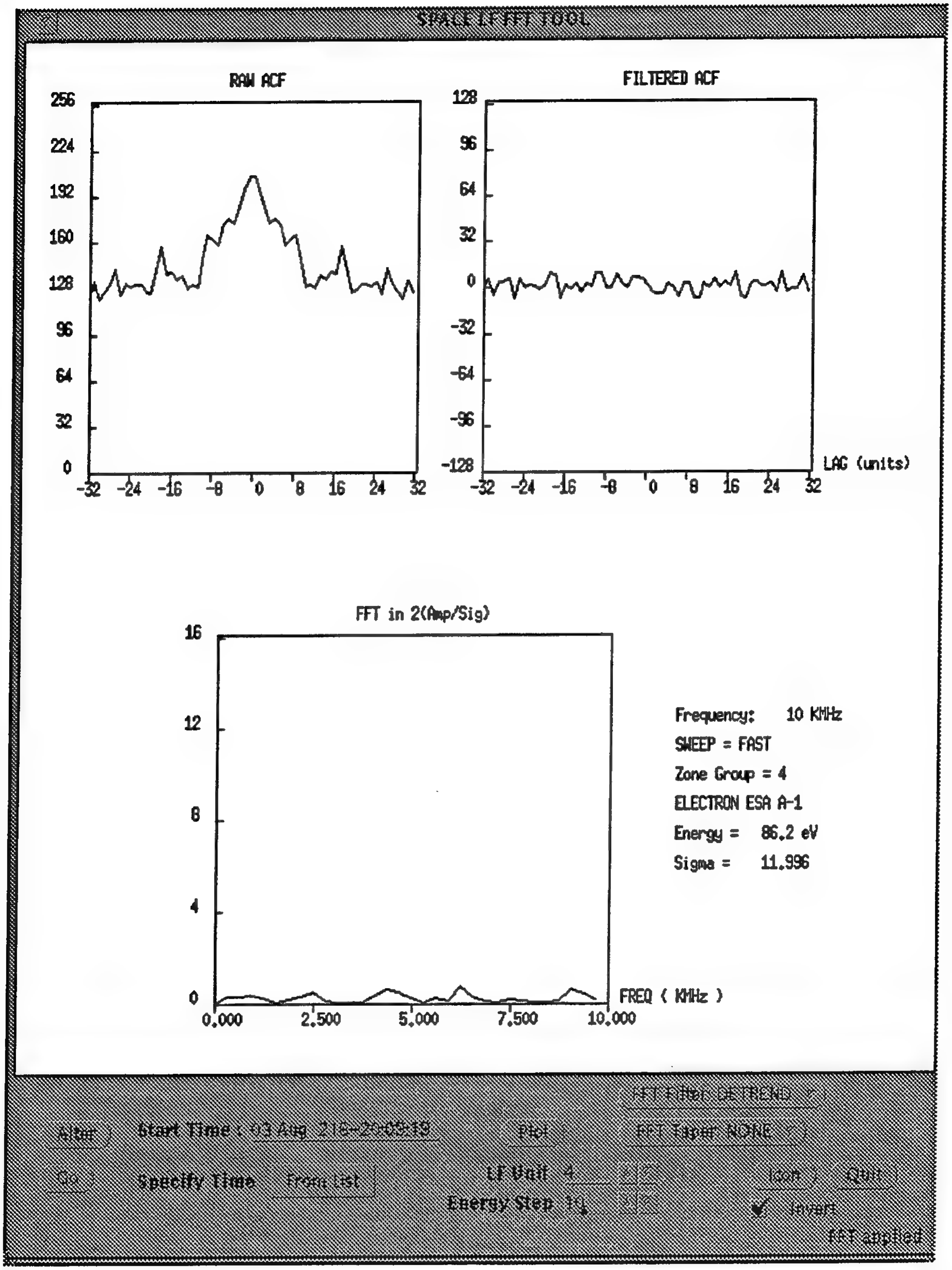

Figure 4. ACF and FFT processing tool of LF SPACE data on August 3, 1992 at 20:09:19. The filtering option selected is detrending only and no tapering was applied.

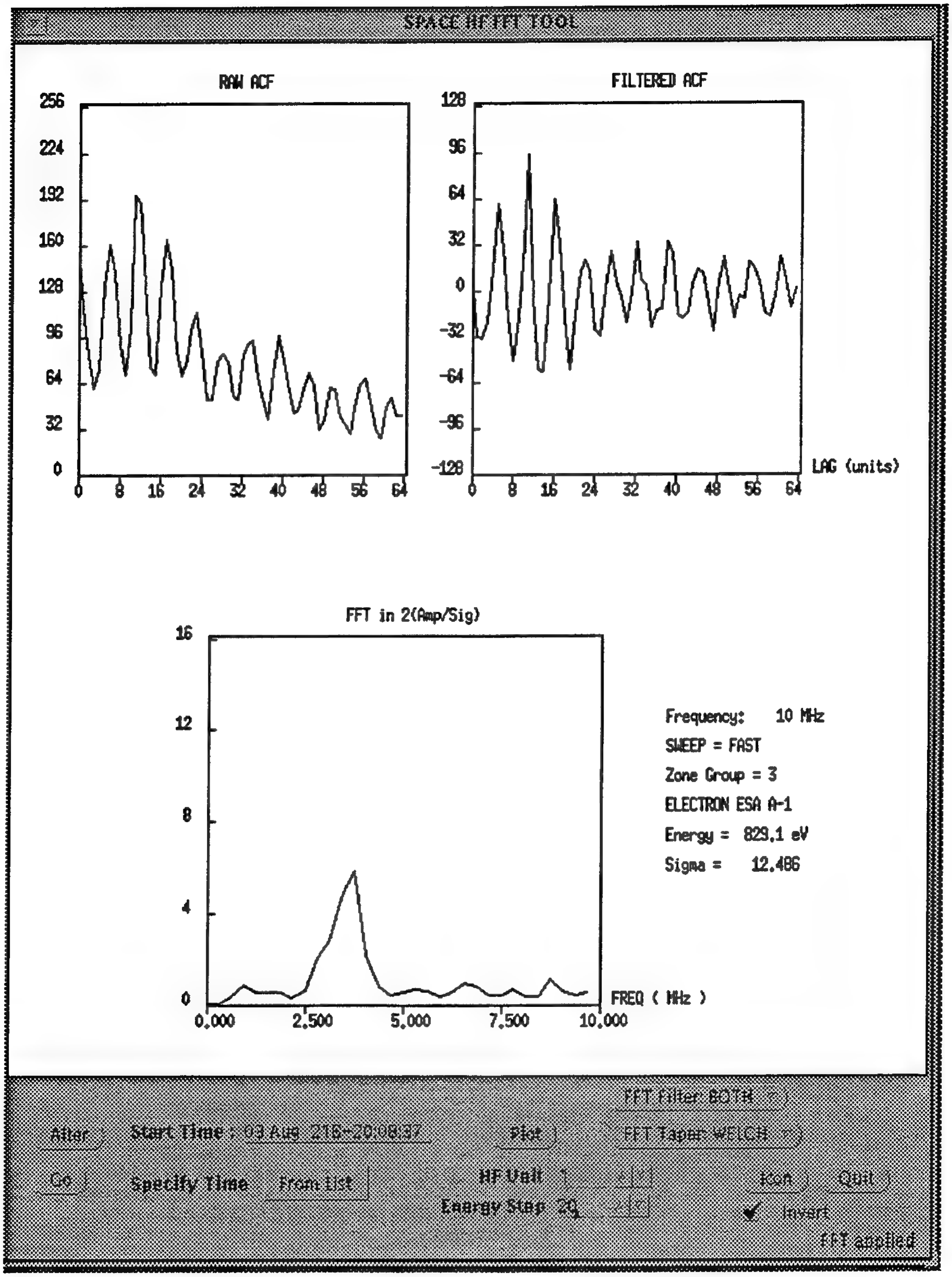

Figure 5. ACF and FFT processing tool on HF data on August 3, 1992 at 20:08:37. Both Despiking and detrending were selected on "Filtering" option and the Welch taper function was applied to the ACF pior to the Fourier transform operation.

6. SPACE ACF SURVEY WINDOW

The ACF/FFT survey window is designed to allow for large amounts of ACF data to be displayed and surveyed. The main display compresses spectral information from each autocorrelation function into a single color coded point. The spectrum of each ACF at 32 energy levels is analyzed, and the maximum spectral intensity divided by one-half sigma is displayed both as a function of energy and frequency. One spectrogram presents the spectral intensity for each energy level with respect to frequency, and a second presents the maximum intensity for each frequency as a function of energy. In this way, spectra resulting from true events can be spotted quite readily.

The window is initiated by choosing a particular start time. In Figure 6, the start time is 20:10 on August 3, 1992. Also selected at initialization, is whether the data should be displayed from ESA A or ESA B, and whether the spectra should be high frequency electrons, low frequency electrons, or low frequency ions. The three channels of either ESA A or ESA B are displayed simultaneously, and the species and/or ESA can be changed at any point during the survey. When the change is made, the same data period will be displayed. Also, when the initialization window is recalled during the survey, the time appearing will be the current time in the survey, so that backing up or changing the precise position of the survey window can be done easily. The intensity is represented by a 32-color display on a linear scale. A total of one-half hour of data is displayed at one time. Also displayed at the bottom of the window is the frequency range of the detectors and the zone group. These are indicated by bars of yellow on a field of blue.

A click in any of the spectral intensity windows records and displays the particular time of that spectra. When the "FFT" button is subsequently pressed, the complete spectrogram for this point in time is displayed in a second window, as is shown in the left panel of Figure 7 for Unit 1 at 20:08:48. This power spectrum is represented in the same units, spectral intensity divided by one-half sigma, in the same 32-color spectrogram. Also given are the unit number, the day and the time of the spectrum, as shown in Figure 7. From this window, one can advance forward or retreat in time and unit number so that the surrounding spectra can also be examined. By examining the entire spectra at points where the maxima suggest significant events, one can further identify interesting features. Clicking within the second "FFT" window calls up a third window (right panel of Figure 7) giving the line plot of the spectrum for the particular energy channel that has been clicked upon. The line plot option is valuable in the determination of the precise frequency of a peak, and whether or not harmonics are present.

The data source for the FFT Survey are the HF and LF data files, which contain the previously processed spectra. Because of the necessity of displaying one-half hour of data at one time, special logic is needed to switch between one file and another. When a switch is made, the same half-hour of data is displayed first from one file and then from the next. The display has the capability of beginning at any integral value of UT minutes. Data gaps are indicated by empty spectrograms and are accounted for in the presentation. In Figure 6, a data gap is present from approximately 20:12 to 20:16:30.

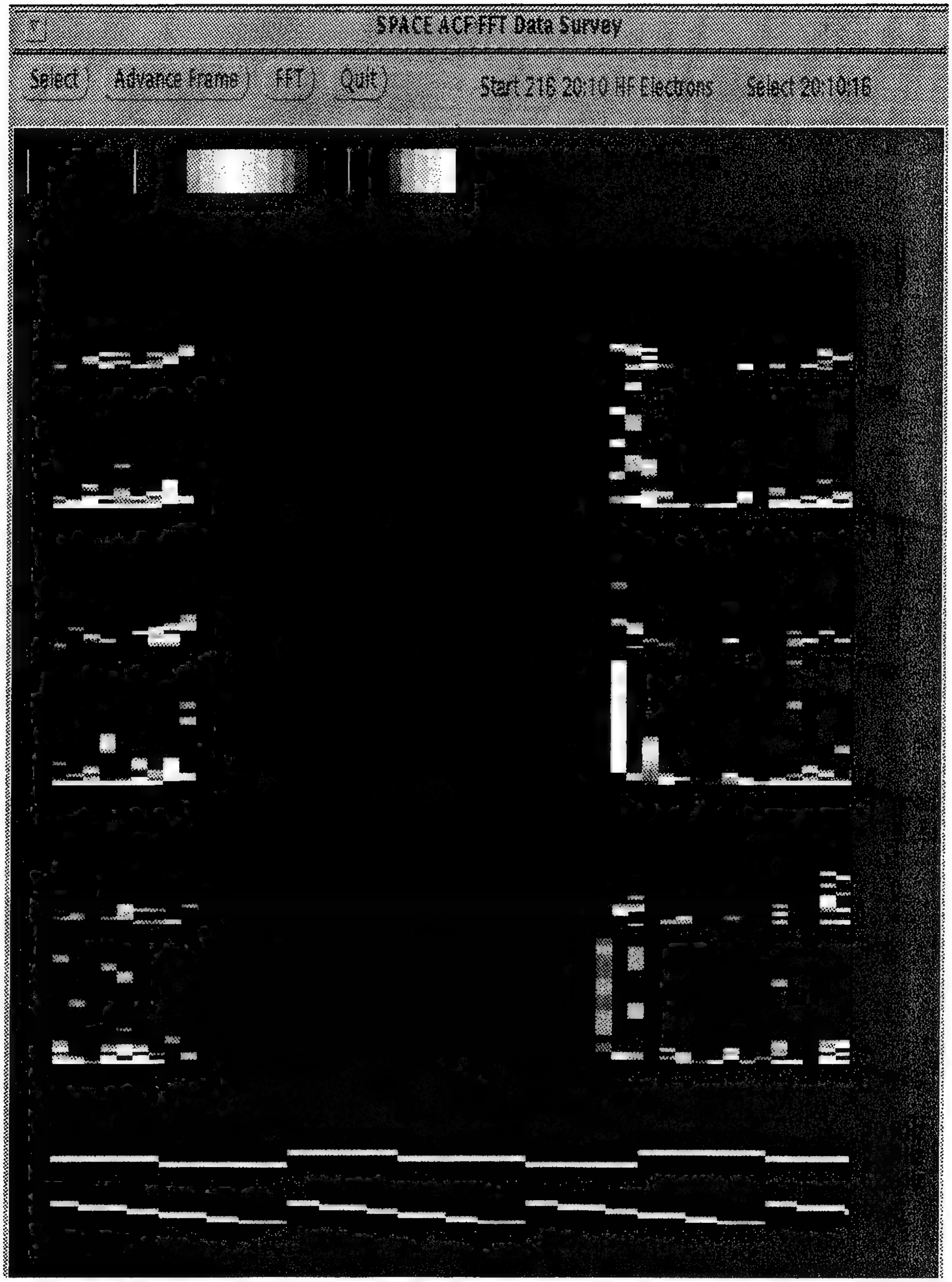

Figure 6. SPACE FFT survey raster color display of HF electrons for Julian day 216. The Energy and Frequency at peak FFT amplitudes are shown for ESA units 0-2. The Bottom pannels show the Maximum Frequency (0.625, 2.5, or 10MHz), and the Zone Group (0-5) for the same time interval.

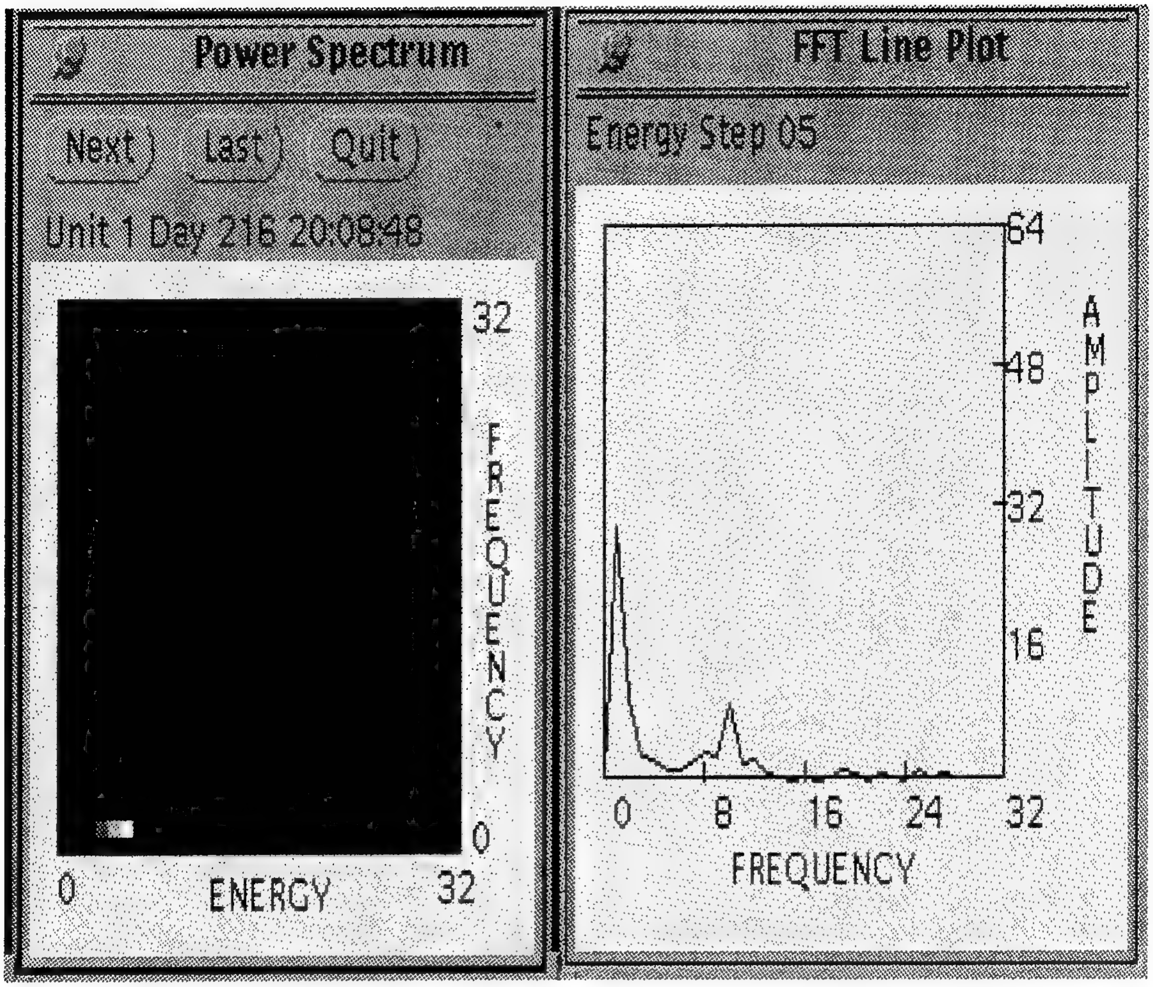

Figure 7. Raster image of the power spectrum (left panel) and line FFT spectrum plot (right panel) for energy step 05 on Julian day 216 at 20:08:48. The raster image on the left panel is a pop-up X windows, which was selected by pressing the right mouse button in Figure 6 at the time shown. The right panel pops up when the right mouse button is clicked at an energy step (0-31) in the raster image of the power spectrum (left panel).

7. FPEG AND ENVIRONMENTAL FREQUENCIES WINDOW

The Fast Pulsed Electron Generator (FPEG) electron beam and Environmental Frequencies window displays the status of the gun along with various environmental parameters. This is a companion window to the ACF Survey window in the SPREE toolkit package and displays the same time interval. It is initialized by selecting the time for the beginning of the survey, which can be adjusted to the nearest UT minute.

Figure 8 shows the top panel of the survey plot, which displays the frequency of the gun as a histogram. The histogram is drawn on a log scale, so that the lowest tick mark is one order of magnitude lower than the lowest non-zero value for FPEG frequency. An empty panel at any point in time signifies that the gun is not operating. In Figure 8, this occurs from approximately 20:11:30 to 20:16:30. Clicking within this panel activates a label on the top of the plot which indicates the UT corresponding to the clicked spot and the precise FPEG frequency in Hz. In Figure 8, the FPEG frequency has a value of 2.48e-02 Hz at 20:11:10. Directly below the FPEG frequency panel is a panel giving the FPEG duty cycle, from 0% to 100%. As with the panel above, clicking here reports the UT at the click point and the precise value of the duty cycle corresponding to this UT. Data for these two panels are obtained from the "fpeg_tab.words" file on the SUN SPARC station. Below the duty cycle panel, the derived FPEG pitch angle is displayed in degrees. This is the angle between the gun and the magnetic field, as obtained from the "fpeg_pitch.dat" file, also on the SUN SPARC station. The scale for this plot is variable.

Below the FPEG panels are four environmental frequency panels. The first two of these give the electron plasma and gyro-frequencies. The electron plasma frequency is obtained from the plasma density recorded in the "tss_iri.dat" file. The frequency is in cycles per second. The electron gyro-frequency is derived from data in the "amagnew.dat" file and is also in cycles per second. These are reported on a log scale. Below these are corresponding panels for the plasma frequency and gyro-frequency of oxygen ions. As with the other panels, clicking in any of these panels reports the precise value and UT of the quantity in question.

The bottom panel of the plot gives the elevation of the magnetic field in degrees. This is defined as the arc cosine of the z-component of the magnetic field divided by its magnitude. The scales on this and the panels above it adjust automatically, depending on the range of values of the parameters.

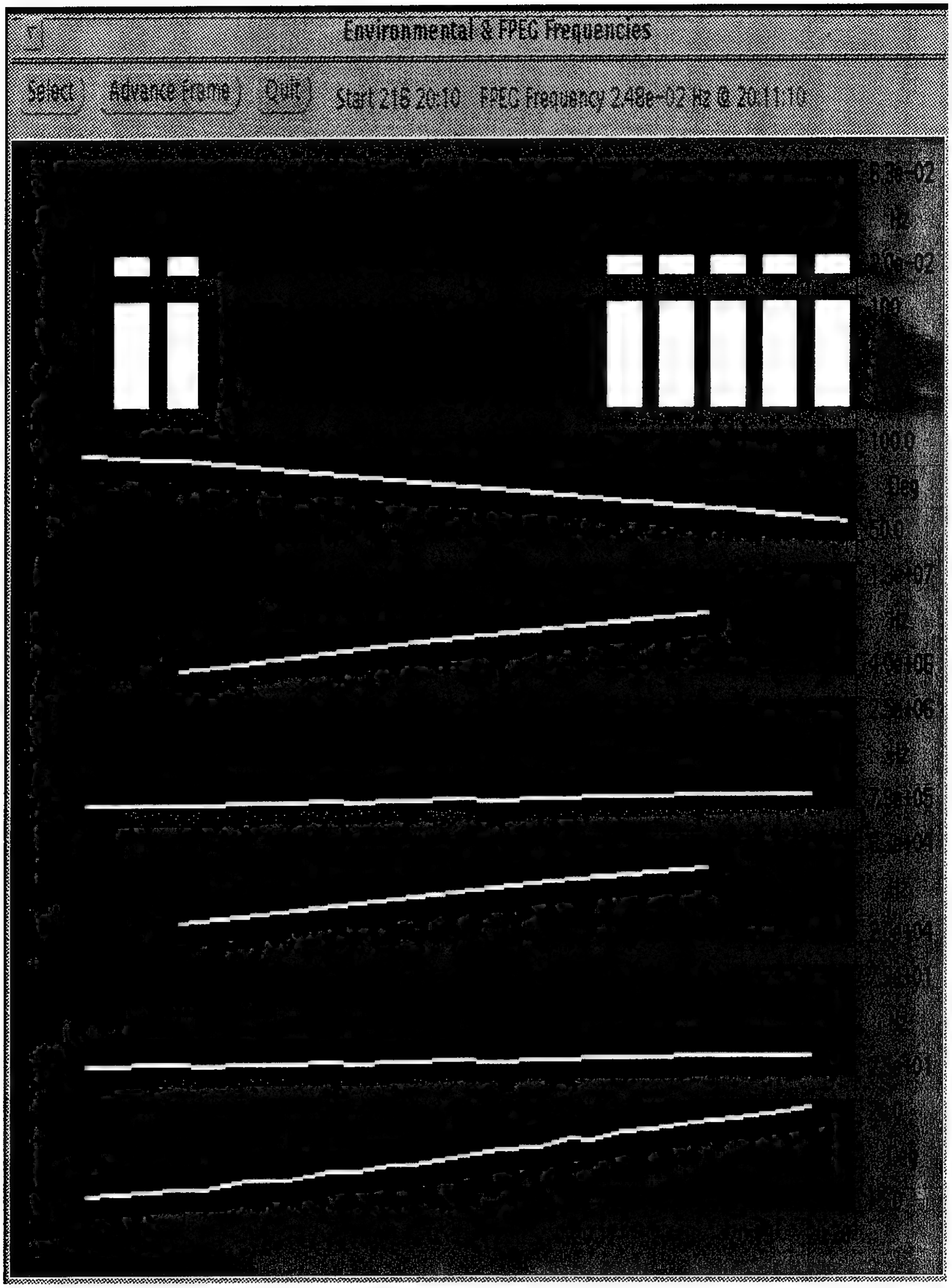

Figure 8. Environmental and FPEG frequencies color display on day 216 starting at 20:10.

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APPENDIX A. PROCESSING ALGORITHMS OF SPACE ACF

A SPACE FFT tool displays line plots of raw ACF, filtered ACF, and their FFT amplitude spectrum. The X Window display allows the selection of options for the processing method in the filtering stage, and the tapering method used to obtain the FFT transforms. These filtering schemes are used to edit noisy segments in some ACF samples. Also, windowing or tapering may be used to remove spectral leakage in the FFT spectrum. The algorithms used in the processing of ACF HF and LF SPACE correlation measurements are described below.

A.1 HF SPACE ACF

Each correlation sequence ACF SPACE HF ρ has 64 lags, or

$$\rho(i),\ i=1,\ 2,\ \ldots,\ 64.$$

A.1.1 Sample Correction at 64th lag

The ACF sample at the last lag is noisy. Sample at the last lag (# 64) is replaced by the sample in the previous lag (# 63).

$$\rho(64) = \rho(63)$$

A.1.2 Despiking

All the algorithms to detect and remove spikes consider 5 samples at a time. The middle sample is tested to determine if it is a spike. We consider a sample to be a spike if the absolute difference between this sample and each of the 2 preceding and 2 following samples exceed a threshold value of θ. The threshold value θ is either 2050 or 300 depending on whether the spikes being tested are considered large or small. Why do we consider 5 samples? This may be necessary to avoid despiking a strong sinusoidal signal at high frequencies. In filtering out the spikes, the approach is to first remove large spikes, then check and correct for roll-over, then filter out small spikes. Finally, any spike detected in the first lag, and not affected by the spike filtering approach above, is removed using a similar approach to be described below. Note that no more than 3 spikes are filtered when considering small or large spike removal.

The spike detection and filtering is explained in more details in the following steps.

Step 1

The algorithm to remove large spikes is applied first. The threshold value θ_L = 2050. Consider an autocorrelation sequence $\rho(i)$, i=1, 2, ..., 64. To detect and remove samples considered to be spikes, we do the following:

For i = 3,..., 62, compute

$$\Delta_{-2} = | \rho(i) - \rho(i-2) |$$
$$\Delta_{-1} = | \rho(i) - \rho(i-1) |$$
$$\Delta_{+1} = | \rho(i) - \rho(i+1) |$$
$$\Delta_{+2} = | \rho(i) - \rho(i+2) |$$

If ($\Delta_{-2} > \theta_L$ and $\Delta_{-1} > \theta_L$ and $\Delta_{+1} > \theta_L$ and $\Delta_{+2} > \theta_L$) then

$$\rho(i) = \tfrac{1}{2} [\rho(i-1) + \rho(i+1)]$$

Note that if more than 3 samples satisfy the above condition, that is, if more than spikes are detected, then no filtering is actually done on these large "spikes". This precaution is in store just to avoid filtering out real signatures.

Step 2

Apply the roll-over correction algorithm described in Section III.

Step 3

Next, apply the algorithm to detect and remove small spikes. The threshold value in this case is θ_S = 300. Consider an autocorrelation sequence $\rho(i)$, i=1, 2, ..., 64. Detection and removal of spiked samples is done as follows:

For i = 3,..., 62, compute

$$\Delta_{-2} = | \rho(i) - \rho(i-2) |$$
$$\Delta_{-1} = | \rho(i) - \rho(i-1) |$$
$$\Delta_{+1} = | \rho(i) - \rho(i+1) |$$
$$\Delta_{+2} = | \rho(i) - \rho(i+2) |$$

If ($\Delta_{-2} > \theta_S$ and $\Delta_{-1} > \theta_S$ and $\Delta_{+1} > \theta_S$ and $\Delta_{+2} > \theta_S$) then

$$\rho(i) = \tfrac{1}{2} [\rho(i-1) + \rho(i+1)]$$

Step 4

Finally, we check whether or not the first sample in the autocorrelation function is a spike. The threshold value in this case is $\theta_F = 100$. We consider the first six samples of the autocorrelation sequence $\rho(i)$, $i=1, 2, ..., 64$. Detection and removal of a spiked sample in the first lag is done as follows:

First compute

$$\Delta_1 = | \rho(0) - \rho(1) |$$
$$\Delta_2 = | \rho(0) - \rho(2) |$$
$$\Delta_3 = | \rho(0) - \rho(3) |$$
$$\Delta_4 = | \rho(0) - \rho(4) |$$
$$\Delta_5 = | \rho(0) - \rho(5) |$$

and

$$\Delta_A = | \rho(0) - (1/5)\sum_i^5 \rho(i) |$$

The sample in the first lag is considered a spike if the following condition is satisfied. If so, then the sample is replaced by the mean of the next 5 lags.

If ($\Delta_1 > \theta_F$ and $\Delta_2 > \theta_F$ and $\Delta_3 > \theta_F$ and $\Delta_4 > \theta_F$ and $\Delta_5 > \theta_F$ and $\Delta_A > \theta_F$) then

$$\rho(0) = (1/5)[\sum_i^5 \rho(i)]$$

Again, note that if more than 3 samples were taken as spikes in Step 3 and Step 4 combined, then no filtering is actually done on these small "spikes".

A.1.3 Roll-Over Correction

This corrects for the loss of the most significant bit when the ACF counts become large and exceed the 12-bit word. The detection and correction of roll-over samples is done as follows

For $i=63,..., 1$,
 if($| \rho(i) - \rho(i+1) | > | \rho(i) + 4096 - \rho(i+1) |$) then
  $\rho(i) = \rho(i) + 4096$

Note that this correction is applied after despiking of large spikes is completed. The roll-over correction does not work when large spikes are still present in the ACF data.

A.2 ACF SPACE LF

Each of the LF SPACE correlation sequences is stored in 32 lags. To obtain the two-sided correlation sequence, the available correlation samples are folded over. Hence, the correlation sequence is expressed as

$\rho(j)$ for lags $j = -31, \ldots, 0, 1, \ldots, 32$

where

$\rho(j) = \rho(1-j), j = 1, \ldots, 32.$

To simplify the notation, we consider the ACF samples to have lags ranging from 1 to 64. No despiking is done on the LF correlation sequences. The next sections describe options that may be applied to either LF or HF SPACE correlation data.

A.3 STANDARD DEVIATION AND MEAN REMOVAL

The standard deviation (σ) is obtained by computing the ACF mean value. It equals the square-root of the sample mean. The mean is given by

$$\mu = (1/64) \cdot \sum_i \rho(i), \; i = 1, \ldots, 64$$

and the standard deviation is

$$\sigma = sqrt(\mu)$$

A.4 DETRENDING

Detrending may be used to filter out the low frequency components for either LF or HF correlation SPACE data. It is essentially a high pass 3rd Butterworth discrete-time filter with a cut-off frequency at the 2nd harmonic. The class of low-pass Butterworth discrete-time filters has a frequency response H(f) whose magnitude squared has the form

$$| H(f) |^2 = 1 / \left[1 + \left(tan(\pi f) / tan(\pi f_c) \right)^{2N} \right]$$

The parameter N is the order of the filter. At $f = f_c$, $| H(f) |$ is $1/\sqrt{2}$ times the gain at $f=0$, independent of the order of the Butterworth filter. Butterworth filters are also referred to as maximally flat frequency responses. The equation above is for a low-pass Butterworth filter. The high-pass Butterworth filter is easily obtained from the low-pass filter. It is given by

$$1.0 - | H(f) |$$

The input correlation sequence is passed through the Butterworth discrete-time filter in order to remove the trend.

A.5 AMPLITUDE SPECTRAL RESPONSE

Using the FFT algorithm, we compute the discrete Fourier transform (DFT) of the ACFs. To obtain the amplitude. The DFT is defined by

$$F_k = (1/N) \sum_{n=0}^{N-1} \rho(n) \cdot w(n) \cdot exp[-jk(2\pi/N)n], \; k=0, 1, \ldots, N-1$$

The tapering function is denoted by w(n) and is defined in the next section. The amplitude of the frequency response is simply

$$A_k = sqrt\,(F_k \cdot F_k^*)$$

A.6 TAPERING

Several optional taper or window functions are available to be used with the ACF before Fourier transforming in order to reduce the spectral leakage in the amplitude spectral response. The following windows are available.

Square

$$w(i) = 1.0 \text{ for } i=1, M$$

Welch

$$w(i) = 1.0 - \left[\Big((i-1) - ½(M-1)\Big) / \Big(½(M+1)\Big) \right]^2 \text{ for } i=1, \ldots, M.$$

Bartlett

$$w(i) = 1.0 - 2 \cdot \left| \Big((i-1) - ½(M-1)\Big)/(M-1) \right| \text{ for } i=1, \ldots, M.$$

Gaussian

$$w(i) = exp\left\{ -½\left[2 \cdot \alpha \cdot \Big((i-1) - ½(M-1)\Big)/(M-1)\right]^2 \right\} \text{ for } i=1, \ldots, M.$$

Parzen

$$w(i) = 1.0 - \left| \Big((i\text{-}1) - \tfrac{1}{2}(M\text{-}1)\Big) / \Big(\tfrac{1}{2}(M+1)\Big) \right| \quad \text{for } i=1, \ldots, M.$$

Hamming

$$w(i) = 0.54 - 0.46 \cdot \mathit{cos}\Big[\big(\pi(i\text{-}1)\big) / \big(\tfrac{1}{2}(M\text{-}1)\big) \Big] \quad \text{for } i=1, \ldots, M.$$

Hanning

$$w(i) = 0.5 - 0.5 \cdot \mathit{cos}\Big[\big(\pi(i\text{-}1)\big) / \big(\tfrac{1}{2}(M\text{-}1)\big) \Big] \quad \text{for } i=1, \ldots, M.$$

A.7 NORMALIZE THE AMPLITUDE SPECTRUM

The amplitude spectrum is normalized by half the standard deviation ($\frac{1}{2}\sigma$), which was computed in section 3.3, to obtain:

$AMP(f)/(\frac{1}{2}\sigma)$